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COMPARISON OF THREE-DIMENSIONAL NEUTRON FLUX CALCULATIONS FOR MAINE YANKEE

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ABSTRACT

Calculations have been performed on the Maine Yankee Power Plant to obtain three-dimensional neutron fluxes using the spatial synthesis with the two-dimensional discrete ordinates code DORT (Ref. 1), the three-dimensional discrete ordinates code THREEDANT (Ref. 2) and the three-dimensional Monte Carlo code MCNP (Ref 3). Neutron fluxes are compared for energies above 0.1 MeV and 1.0 MeV as well as dpa. Results were obtained at the Yankee dosimetry locations and special test regions within the pressure vessel, in the reactor cavity, and in a shield tank detector well.

1.0 Background

The computation of neutron fluxes from the core out to and within the shield tank has always been a difficult problem to solve accurately and easily. For example, traditional methods for use in the analysis of pressure vessel damage resulting from neutron irradiation have primarily relied on two-dimensional transport calculations and a spatial-synthesis methodology to generate three-dimensional fluxes from the results of two two-dimensional calculations. Such synthesis methodology makes assumptions on the spatial separability of the neutron flux and results in additional analysis uncertainty. Three-dimensional calculations offer the possibility of obtaining the required neutron fluences more efficiently and more accurately.

The Reactor Physics Group at Yankee Atomic Electric Company and the Radiation Transport Group at Los Alamos National Laboratory have investigated some of these issues through calculations on Maine Yankee. This effort was divided into three parts. This paper presents the results of the final stage of this effort where full-core calculations were made using the three-dimensional codes THREEDANT and MCNP, and the synthesized three-dimensional results obtained from two-dimensional DORT calculations.

2.0 Calculations

The material and geometric bases for these calculations is the Maine Yankee power plant (Ref 4). A one-eighth azimuthal cross section of the reactor, at core midplane, is shown in Figure 1. The axial extent of the core is from -173.61 to +173.61 cm. All three calculations described herein used this basic information as a starting point and then made whatever geometric and material approximations were necessary for the code to be used. Because of the flexibility of the MCNP code, geometric detail is not limited other than in the complexity and size of the input file.

The same XY pinwise power distribution, corresponding to cycle 1, was available for the development of the source for each of the calculational methods. In the axial direction,

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the power distribution was assumed to follow the same distribution for all pins and this corresponded to an azimuthal average of the axial distribution of the outer core assemblies.

Figure 1. Cross-section of Maine Yankee.

Each of the three calculational methods used the SAILOR 47 energy-group library (Ref 5) which is based on ENDF/B Version IV data. In the case of MCNP, the SAILOR data was processed to put it in a format compatible to the multigroup option of the code. The DORT and THREEDANT calculations were performed using a P3 scattering approximation.

The DORT calculations are described in detail in Reference 5. The radial mesh spacing was approximately 0.8 cm in water, 1.3 cm in steel, and 2.5 cm in air; the azimuthal mesh spacing was a uniform 0.5 degrees; and the axial mesh spacing was approximately 1.7 cm. This fine spacing aided in modeling rectilinear components such as the core, core baffle, and dosimetry capsules. The models extended 50 cm radially into the water-filled shield tank, and 50 cm above and below the active fuel elevations. A P3 scattering and a S8 quadrature approximation was used in all DORT calculations. The three-dimensional flux was synthesized from the $R\theta$, RZ , and one-dimensional radial model results via the formula (Ref 6):

$$\phi(g, r, \theta, z) = (\phi(g, r, \theta)\phi(g, r, z))/\phi(g, r) .$$

The XYZ THREEDANT model is essentially the same as the MCNP model described below in all its geometric details. The FRAC-IN-THE-BOX code (Ref 7) is used to specify the combinatorial geometry description and to resolve this onto a specified XYZ spatial mesh. This three-dimensional volume fraction geometry description is accepted as input to THREEDANT code which performs the transport calculation using the discrete ordinates method. The resulting XYZ spatial mesh is 125 x 110 x 60 and the computation was done with 47 energy groups, P3 scattering approximation, and S8 angular quadrature. This angular quadrature was found to be adequate for the problem based on two-dimensional studies of the system at the core mid-plane.

MCNP calculations were performed using a one-eight azimuthal model that extended from -200.0 to +200.0 cm in the axial direction. The model extended 46 cm into the shield tank water. Rectilinear and curved surfaces were modeled as they exist. The core source was modeled as sixty volumes for each of the twenty-five axial zones for a total of 1500 source regions. Variance reduction techniques used in the calculations included geometry biasing of the source, and also geometry splitting and Russian Roulette, and energy splitting in the transport of the neutrons from the core to the points of interest.

3.0 Comparison of Results

Neutron fluxes greater than 1.0 MeV and greater than 0.1 MeV and dpa rates were determined for a number of test regions as well as the Maine Yankee dosimetry capsules. For each region the dpa rate was determined by folding the 47 energy-group flux with the dpa cross section to obtain the dpa rate. The test regions are located between the core and the outside of the pressure vessel and are within 25 cm of the core midplane. These regions were designed to provide a means of further comparing the methods at radial locations on either side of the surveillance dosimetry. In addition, these test regions were designed to allow clean comparisons between the various solutions. This was done by making two separate MCNP calculations for the test regions; in the first the DORT R θ Z test regions were modeled exactly in MCNP and in the second calculation the THREEDANT XYZ test regions were modeled exactly in MCNP. The R θ test region boundaries are indicated in Figure 1 for the test regions 1, 2, 3A, 4, 5, 6, 8, and 9. The corresponding THREEDANT test regions have boundaries that are close to these, but not identical, and thus the DORT and THREEDANT results for the test regions are only compared with the respective MCNP results and not with each other.

The dosimetry regions 7, 10, 11, 13, 14, and 15 were each modeled as accurately as possible for use with each calculational method. (For reference to the Yankee paper (Ref 4), the dosimetry regions 10, 11, 13, and 14 correspond to the accelerated capsules A35 and A25 and the wall capsules W253 and W263, respectively.) Dosimetry region 7 is in the cavity and 15 is in a detector well.) Therefore a comparison of the results for these dosimetry regions as determined by each of the different methods is an indication both of the modeling limitations and the calculational methods. The dosimetry region locations, in terms of the R θ boundaries are shown in Figure 1. Results were determined for three axial locations for each of the dosimetry regions; below, above, and approximately at the core midplane. For regions 10 and 11 the off midplane results were from -72.0 to 105 cm, for regions 13 and 14

they were from -80.0 to 94.0 cm, for region 7 they were from ± 36.0 cm, and for region 15 from ± 173 cm.

The average DORT-to-MCNP ratios for the DORT test regions is 0.93 and the average THREEDANT-to-DORT ratios for the THREEDANT test regions is 1.02. The individual data for these test regions are contained in Table 1. Table 2 contains the individual data for the dosimetry regions within the pressure vessel. The average DORT-to-MCNP and THREEDANT-to-MCNP ratios for these dosimetry regions, are 0.87 and 1.00 respectively. The dosimetry regions outside the pressure vessel yields average DORT-to-MCNP and THREEDANT-to-MCNP ratios of 0.98 and 1.19 respectively. The individual data for these test regions are contained in Table 3.

4.0 Conclusions

Three-dimensional neutron transport calculations have been performed for Maine Yankee using the discrete ordinates code THREEDANT and the Monte Carlo MCNP and the SAILOR 47 neutron-group cross-section library. These results have been compared to the three-dimensional results obtained via a spatial synthesis method using the discrete ordinates code DORT. The results indicate that the THREEDANT and MCNP results predict results that are higher on the average than the DORT spatial synthesized results. The agreement shown for the test regions adjacent to the core is good. This provides a basic confidence that the various methods have done a good job of modeling the core, power distribution, and the general geometry. The MCNP results tend to be consistently slightly higher which may result from the modeling of the power distribution, or the geometry, and/or the difference in the transport of the neutrons. It is noted that in Reference 4, the comparison of DORT results to experimental results is that the calculated-to-experimental ratio is approximately 0.85 for the accelerated and wall capsules.

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TABLE 1
Comparison of Results at Test Regions

Reg.	Quantity	DORT ^a	MCNP ^b	$\frac{DORT}{MCNP}$	3DANT ^c	MCNP	$\frac{3DANT}{MCNP}$
1	$\phi(> 1.0)^d$	5.20+12	5.53+12(.009)	0.94	5.62+12	5.59+12(.009)	1.01
1	$\phi(> 0.1)^e$	1.09+13	1.15+13(.010)	0.94	1.20+13	1.19+13(.012)	1.01
1	dpa rate	7.80-9	8.25-9(.016)	0.94	8.40-9	8.45-9(.014)	0.99
2	$\phi(> 1.0)$	5.64+12	5.94+12(.007)	0.95	5.49+12	5.36+12(.009)	1.02
2	$\phi(> 0.1)$	2.03+12	1.29+13(.007)	0.94	1.17+13	1.14+13(.012)	1.02
2	dpa rate	1.36-9	8.78-9(.012)	0.96	8.20-9	7.98-9(.014)	1.03
3	$\phi(> 1.0)$	8.68+11	9.54+11(.011)	0.91	9.17+11	9.13+11(.012)	1.00
3	$\phi(> 0.1)$	2.03+12	2.10+12(.012)	0.92	2.04+12	2.06+12(.015)	0.99
3	dpa rate	1.36-9	1.46-9(.021)	0.90	1.38-9	1.41-9(.019)	0.98
4	$\phi(> 1.0)$	8.975+11	9.77+11(.008)	0.92	8.71+11	8.77+11(.012)	0.99
4	$\phi(> 0.1)$	2.03+12	2.22+12(.009)	0.91	1.94+12	1.91+12(.014)	1.01
4	dpa rate	1.36-9	1.45-9(.015)	0.93	1.32-9	1.29-9(.020)	0.91
5	$\phi(> 1.0)$	2.64+10	3.06+10(.012)	0.88	4.08+10	3.82+10(.017)	1.07
5	$\phi(> 0.1)$	5.47+10	6.27+10(.014)	0.87	8.70+10	7.95+10(.018)	1.09
5	dpa rate	4.15-10	4.75-11(.023)	0.87	6.47-11	5.93-11(.027)	1.09
6	$\phi(> 1.0)$	9.11+9	9.55+9(.013)	0.95	1.39+10	1.31+10(.018)	1.06
6	$\phi(> 0.1)$	3.64+10	3.21+10(.019)	1.13	4.76+10	8.18+10(.580)	0.58
6	dpa rate	1.68-11	1.69-11(.026)	0.99	2.39-11	2.23-11(.030)	1.07
8	$\phi(> 1.0)$	2.47+12	2.63+12(.011)	0.94	2.48+12	2.41+12(.014)	1.03
8	$\phi(> 0.1)$	4.74+12	5.17+12(.013)	0.92	4.79+12	4.74+12(.017)	1.01
8	dpa rate	3.71-9	4.01-12(.021)	0.93	3.72-9	3.63-9(.024)	1.02
9	$\phi(> 1.0)$	1.45+11	1.62+11(.014)	0.89	1.51+11	1.58+11(.021)	0.96
9	$\phi(> 0.1)$	3.86+11	4.34+11(.013)	0.89	4.01+12?	4.23+11(.020)	0.95
9	dpa rate	2.20-10	2.54-9(.027)	0.86	2.29-10	2.32-10(.029)	0.99

^aThe spatial synthesis method using DORT.

^bValues in parenthesis are fractional errors, a measure of precision and not accuracy of the calculation.

^cThe three-dimensional, discrete ordinates code, THREEDANT.

^dNeutron flux for neutrons with energies greater than 1.0 MeV.

^eNeutron flux for neutrons with energies greater than 0.1 MeV.

TABLE 2
Comparison of Results at In-Vessel Dosimetry Locations

Region	Quantity	DORT ^a	3DANT ^b	MCNP ^c	$\frac{DORT}{MCNP}$	$\frac{3DANT}{MCNP}$
10A	$\phi(> 1.0)^d$	2.69+11	2.77+11	2.76+11 (.042)	0.97	1.00
10A	$\phi(> 0.1)^e$	6.04+11	6.29+11	6.58+11 (.41)	0.91	0.96
10A	dpa rate	3.94-10	4.17-10	4.25-10 (.060)	0.93	0.98
10B	$\phi(> 1.0)$	3.20+11	3.47+11	3.45 (.040)	0.93	1.00
10B	$\phi(> 0.1)$	7.15+11	7.86+11	8.34+11 (.045)	0.86	0.94
10B	dpa rate	4.68-10	5.09-10	5.17-10 (.059)	0.90	0.98
10C	$\phi(> 1.0)$	3.08+11	3.26+11	3.72+11 (.046)	0.83	0.88
10C	$\phi(> 0.1)$	6.87+11	7.62+11	7.81+11 (.042)	0.87	0.98
10C	dpa rate	4.50-10	6.49-10	4.78-10 (.067)	0.94	1.03
11A	$\phi(> 1.0)$	3.54+11	3.67+11	3.91+11 (.027)	0.90	0.94
11A	$\phi(> 0.1)$	8.23+11	8.57+11	9.42+11 (.028)	0.87	0.91
11A	dpa rate	5.22-10	5.94-10	5.58-10 (.040)	0.94	1.06
11B	$\phi(> 1.0)$	4.21+11	4.59+11	4.84+11 (.028)	0.87	0.95
11B	$\phi(> 0.1)$	9.79+11	1.06+12	1.11+12 (.028)	0.79	0.96
11B	dpa rate	6.21-10	6.77-10	6.56-10 (.036)	0.95	1.03
11C	$\phi(> 1.0)$	4.05+11	4.44+11	4.52+11 (.028)	0.90	0.98
11C	$\phi(> 0.1)$	9.41+11	1.03+12	1.11+12 (.028)	0.85	0.93
11C	dpa rate	5.97-10	6.49-10	6.84-10 (.045)	0.87	0.95
13A	$\phi(> 1.0)$	2.55+10	3.01+10	3.00+10 (.061)	0.85	1.00
13A	$\phi(> 0.1)$	5.70+10	6.72+10	6.61+10 (.027)	0.86	1.02
13A	dpa rate	3.80-11	4.28-11	4.47-11 (.046)	0.75	0.96
13B	$\phi(> 1.0)$	2.88+10	3.47+10	3.25+10 (.027)	0.88	1.07
13B	$\phi(> 0.1)$	6.43+10	7.75+10	7.43+10 (.028)	0.87	1.04
13B	dpa rate	4.33-11	5.23-11	5.40-11 (.076)	0.80	0.97
13C	$\phi(> 1.0)$	2.72+10	3.31+10	3.12+10 (.028)	0.87	1.06
13C	$\phi(> 0.1)$	6.07+10	7.41+10	7.30+10 (.030)	0.83	1.01
13C	dpa rate	4.08-11	5.064-11	4.80-11 (.048)	0.85	1.05
14A	$\phi(> 1.0)$	2.61+10	3.08+10	2.93+10 (.025)	0.89	1.05
14A	$\phi(> 0.1)$	5.80+10	6.88+10	7.44+10 (.028)	0.78	0.93
14A	dpa rate	3.92-11	4.68-11	4.61-11 (.046)	0.85	1.02
14B	$\phi(> 1.0)$	2.95+10	3.56+10	3.51+ (.028)	0.84	1.01
14B	$\phi(> 0.1)$	6.55+10	7.95+10	7.55+10 (.026)	0.87	1.05
14B	dpa rate	4.43-11	5.36-11	5.52-11 (.056)	0.80	0.97
14C	$\phi(> 1.0)$	2.78+10	3.40+10	3.14+10 (.026)	0.88	1.08
14C	$\phi(> 0.1)$	6.18+10	7.82+10	6.94+10 (.025)	0.89	1.13
14C	dpa rate	4.18-11	5.12-11	4.88-11 (.044)	0.82	1.05

^aThe spatial synthesis method using DORT.

^bThe three-dimensional, discrete ordinates code, THREEDANT.

TABLE 3
Comparison of Results at Ex-Vessel Dosimetry Locations

Region	Quantity	DORT ^a	3DANT ^b	MCNP ^c	$\frac{DOT}{MCNP}$	$\frac{3DANT}{MCNP}$
7A	$\phi(> 1.0)$	4.26+8	5.30+8	4.78+8(0.024)	0.89	1.11
7A	$\phi(> 0.1)$	5.44+9	6.35+9	6.00+9 (.015)	0.91	1.06
7A	dpa rate	1.74-12	2.07-12	1.92-12 (.015)	0.90	1.07
7B	$\phi(> 1.0)$	4.33+8	5.41+8	4.90+8 (.025)	0.88	1.10
7B	$\phi(> 0.1)$	5.54+9	6.51+9	6.09+9 (.014)	0.91	1.07
7B	dpa rate	1.77-12	2.11-12	2.02-12 (.018)	0.88	1.04
7C	$\phi(> 1.0)$	4.27+8	5.39+8	4.95+8 (.024)	0.86	1.09
7C	$\phi(> 0.1)$	5.46+9	6.45+9	6.16+9 (.013)	0.89	1.05
7C	dpa rate	1.75-12	2.09-12	2.46-12 (.219)	0.71	0.85
15A	$\phi(> 1.0)$	1.45+7	1.78+7	1.06 (.082)	1.36	1.67
15A	$\phi(> 0.1)$	9.57+7	8.82+7	1.00+8 (.046)	0.95	0.88
15A	dpa rate	4.14-14	4.14-14	3.45-14 (.054)	1.20	1.28
15B	$\phi(> 1.0)$	4.24+7	5.60+7	3.16+7 (.056)	1.34	1.77
15B	$\phi(> 0.1)$	2.85+8	3.51+8	2.81+8 (.036)	0.98	1.25
15B	dpa rate	1.19-13	1.55-13	1.06-13 (.050)	1.11	1.46
15C	$\phi(> 1.0)$	1.61+7	2.41+7	1.16+7 (.072)	1.39	2.08
15C	$\phi(> 0.1)$	1.06+8	1.06+8	1.10+8 (.056)	0.95	0.96
15C	dpa rate	4.56-14	5.60-14	9.37-14 (.573)	0.49	0.60

^aThe spatial synthesis method using DORT.

^bThe three-dimensional, discrete ordinates code, THREEDANT.

^cValues in parenthesis are fractional errors, a measure of precision and not accuracy of the calculation.